

Cyclicality and fault/fracture controlled dolomitisation

Lower Carboniferous, Great Orme, North Wales

Field Excursion for Geoscience Wales
15th July 2014



Cathy Hollis, University of Manchester

Based on PhD thesis prepared by Alanna Juerges (University of Manchester)

Emergency contact details

Llandudno General Hospital

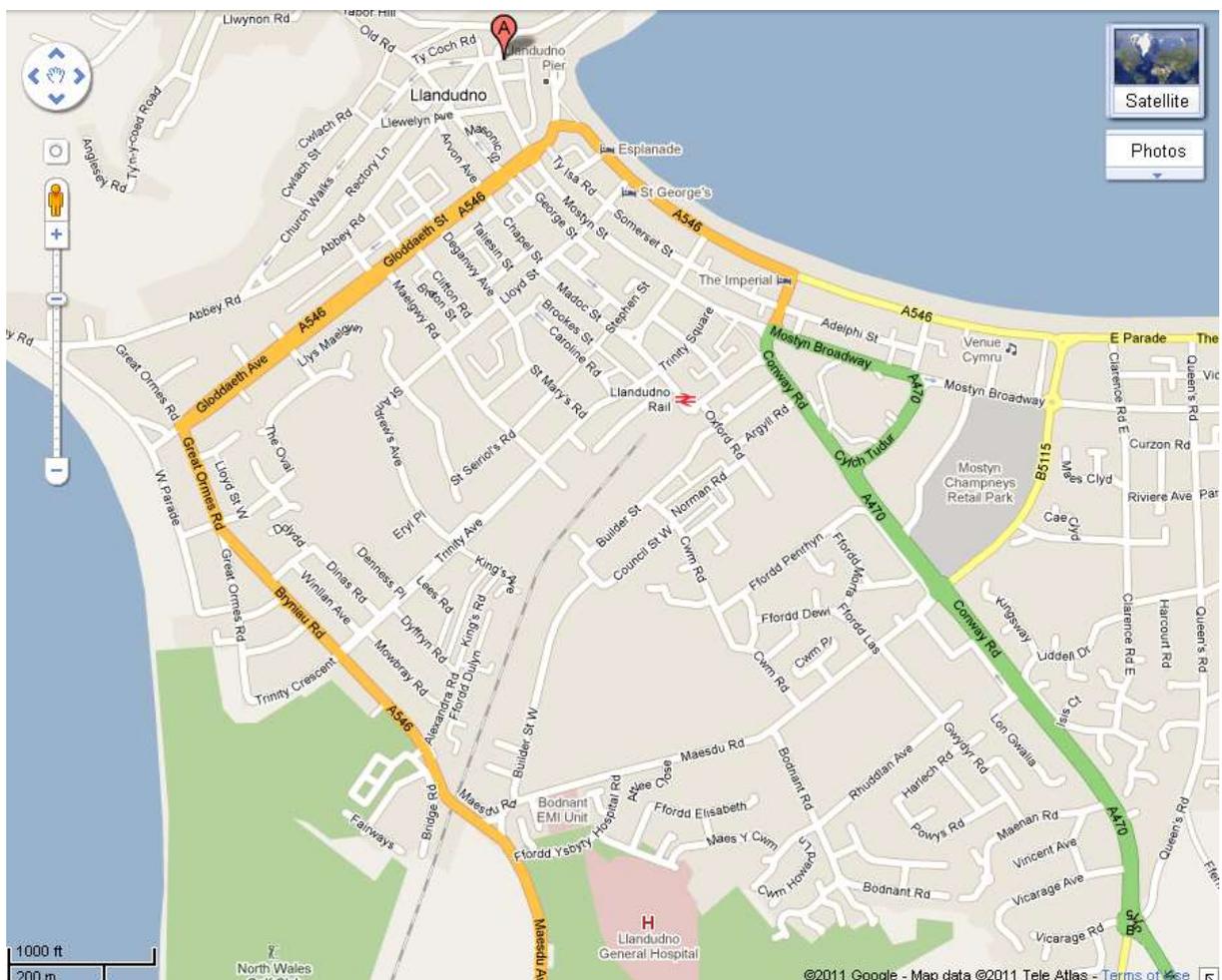
Llandudno, Conwy, LL30 1

Tel: +44 (0) 1492 860066

Emergency Services: 999 (extreme emergency only)

Health and safety

Locations vary and the trip will require some walking. The beach has some potentially slippery rocks and unstable pebbles underfoot. Please be aware that **low tide** is at **7.12pm**. Some outcrops are in close proximity to cliff faces and overhangs so please ensure a hard hat is worn at all times around these localities and avoid standing under overhangs or near open fissures. The summit of the Great Orme is exposed and often subject to high winds, rain or sun, please dress accordingly.



Map of Llandudno, H: hospital.

Aims

The aim of the excursion is to

- Examine the platform margin succession of the Lower Carboniferous (Asbian and Brigantian) limestone succession of the North Wales Platform
- Describe the stacking patterns of upward-shallowing depositional cycles on a shallow marine carbonate platform
- examine the relationship between diagenesis, structure and sedimentology within a partially dolomitised succession.

* Please note that *hammering and sampling is **not** permitted* without prior council consent. The site is a Site of Special Scientific Interest (SSSI) with regards to the rare fauna and flora. Therefore, we must also ask that you do not pick or collect plants or flowers or disturb the local wildlife.

Itinerary

Activities are subject to the weather and tides.

5.30pm	Meet at entrance to Pier (on the promenade)
5.45pm	Overview on Pier, looking at Gt Orme / HSE briefing
6.00pm	Examine Pier Dolomite on the beach
6.45pm	Tollhouse mudstone at Tollhouse caves
7.00pm	Examine facies & cyclicity within Great Orme Limestone
8.30pm	Walk back to pier for final discussion and finish



Figure.1. Great Orme, map of sections (white circles) logged and sampled, with thin sections, prior to 4th March 2011. Yellow circles indicate areas of re-sampling. Numbers are key locations referred to in the text. Image from Google Earth (accessed 29.06.2011).

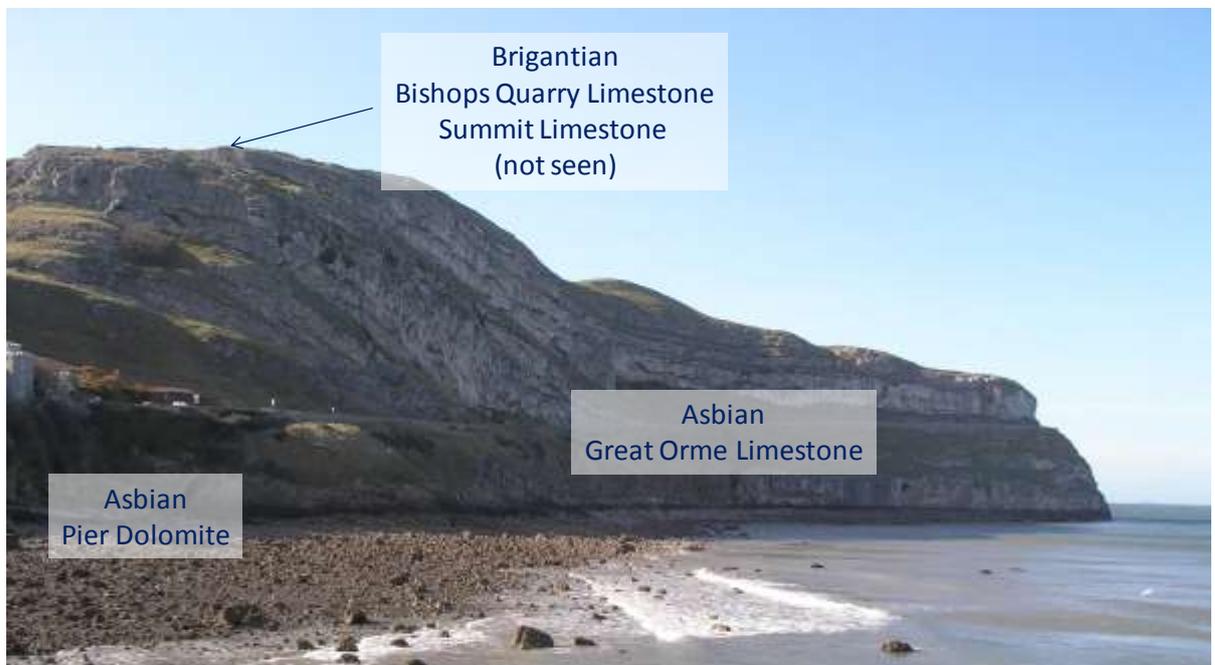


Figure 2. Great Orme from the pier

Schedule

Locality 1: Beach

The Pier Dolomite is Asbian in age and comprises dolomitised crinoidal packstone-grainstone with thin, interbedded mudstone and shale. The dolomitised beds dip to the north-west and contain remnant skeletal debris (coral, particularly *Lithostrotion*, crinoid and echinoderm fragments). The contact between the dolomite and the host limestone is seen at several points in the lowermost part of the section, near the steps, with rafts of undolomitised limestone. The dolomite/limestone contact is typically sharp.

In general, the dolomite is coarsely crystalline and fabric destructive, although in places crinoid and coral debris can still be seen. Over much of the section, the replacive dolomite has been overprinted by centimetre to metre scale zebra dolomite, which has been eroded in places to give prominent fist-sized vugs. The dolomite is commonly cut by fractures, which can be several centimetres wide and filled by several generations of calcite, dolomite and minor Pb-Zn-Cu mineralisation.



Figure 3: Replacive dolomite (brown) and limestone (light grey). Note the sharp termination of the dolomite against the limestone

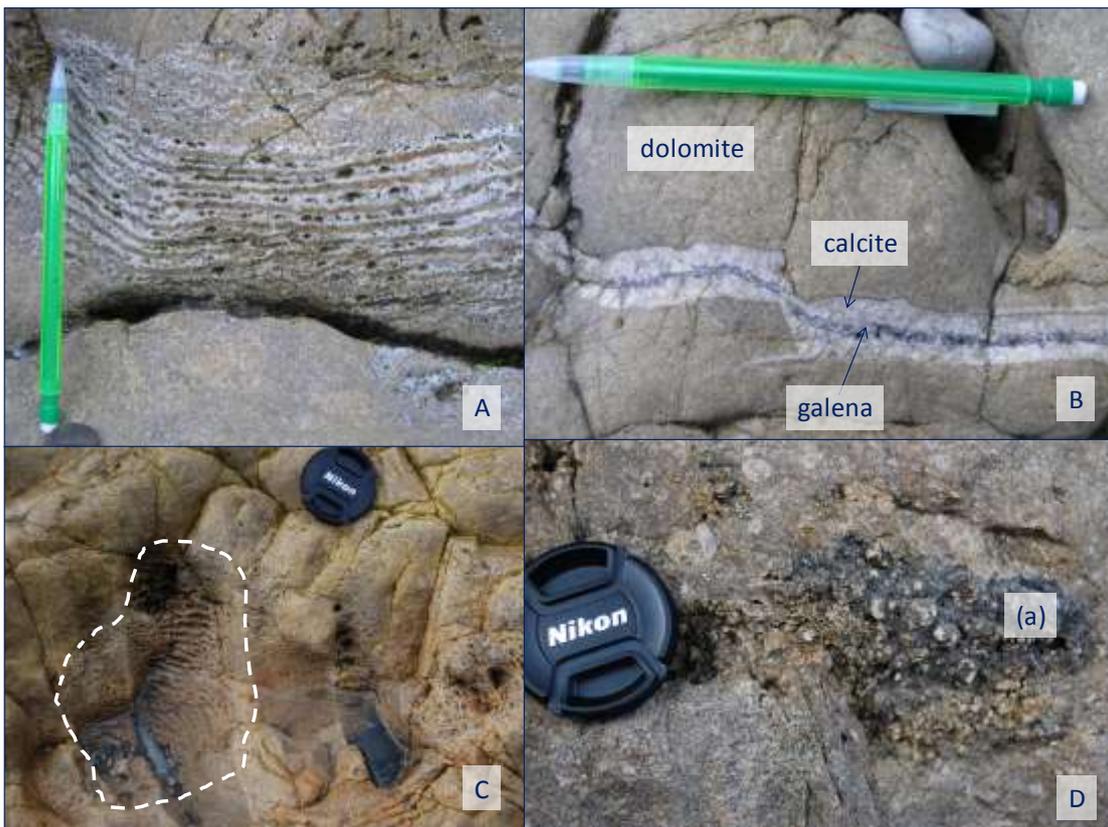


Figure 4 Dolomite textures within the Pier Dolomite. [A] Zebra dolomite, infilled by saddle dolomite, [B] replacive dolomite cross-cut by calcite and galena cemented fracture [C] leached zebra dolomite (outlined) [D] vug in dolomite, infilled by coarsely crystalline dolomite cement



Figure 5 N-S trending fault (shown by white dotted line) with damage zone, including an echelon zebra dolomite, shown in red box, cross-cut by malachite cemented fractures and fault breccia, shown in orange box, in which rounded clasts of dolomite are coated by dolomite, calcite and malachite

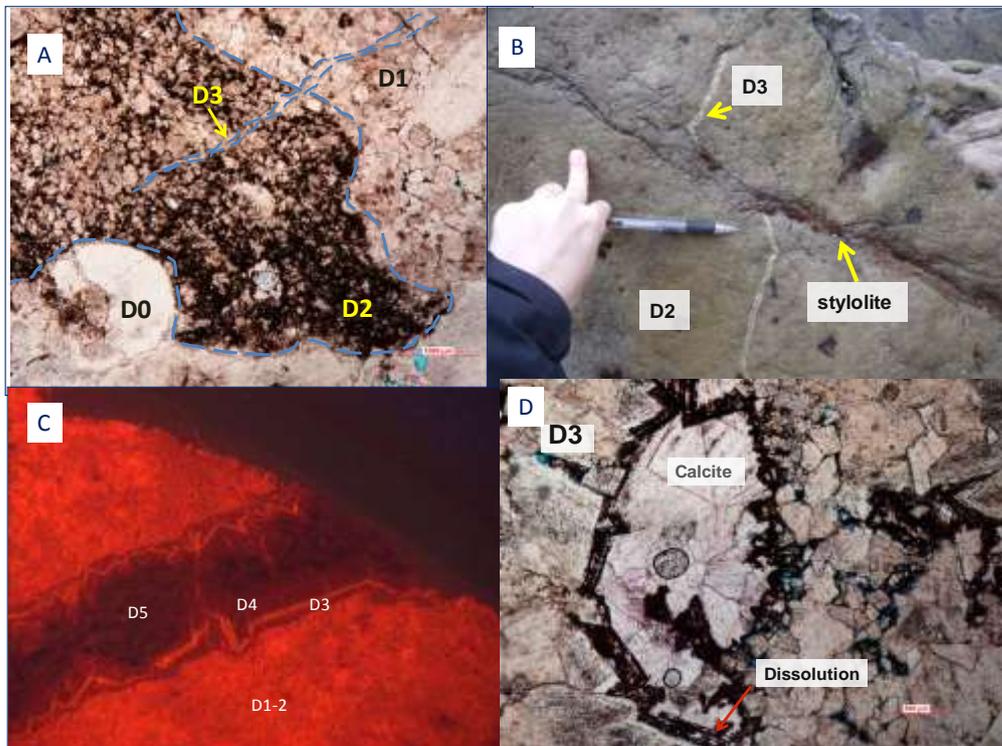


Figure 6 Petrographic texture of replacive (D0-D2) dolomite and fracture filling dolomite (D3-5), with post-dolomitisation calcite

Locality 2: Eastern Toll Road

This section comprises the Great Orme Limestone, which directly overlays the Pier Dolomite and Tollhouse Mudstone. The latter is seen to outcrop at the base of the caves, just on entering the Toll Road. A number of small faults, with evidence for normal and strike-slip movement, can be observed within this section. Both types of fault are often characterised by a halo of dolomite and secondary porosity.

The Tollhouse Mudstone comprises skeletal wackestone and packstone. The Great Orme Limestone

The Great Orme Limestone Fm comprises stacked beds of that form metre- decimetre thick cycles, typically comprising:

- Basal units of bioturbated skeletal wacke/packstone, interpreted to have been deposited in a moderate energy subtidal environment
- Skeletal grainstone beds of variable thickness, locally with uni- and bidirectional cross-bedding, typical of high energy sand-sheets and tidal bars. Interbedded, metre-scale coral-algal boundstones are interpreted to be patch reefs
- Thin beds of algal laminate and skeletal wackestone, deposited in a low energy subtidal-intertidal environment
- An irregular, down-cutting upper contact that is infilled by calcrete and yellow and red palaeosols and/or a matrix-supported chaotic conglomerate. The surface topography is indicative of karstification, with subsequent soil formation

Overall, the Great Orme limestone comprises approximately 10 upward-shallowing, transgressive-regressive cyclical limestone units capped by exposure surfaces and/ or palaeosols. An increase in the development of palaeosols towards the top of the formation. is consistent with falling relative sea level throughout the Asbian (Warren et al., 1984).



Figure 7 Skeletal grainstone and coralline/algal build-ups within Cycles 4-5



Figure 8: Yellow palaeosol and calcrete at the top of Cycle 4

APPENDICES

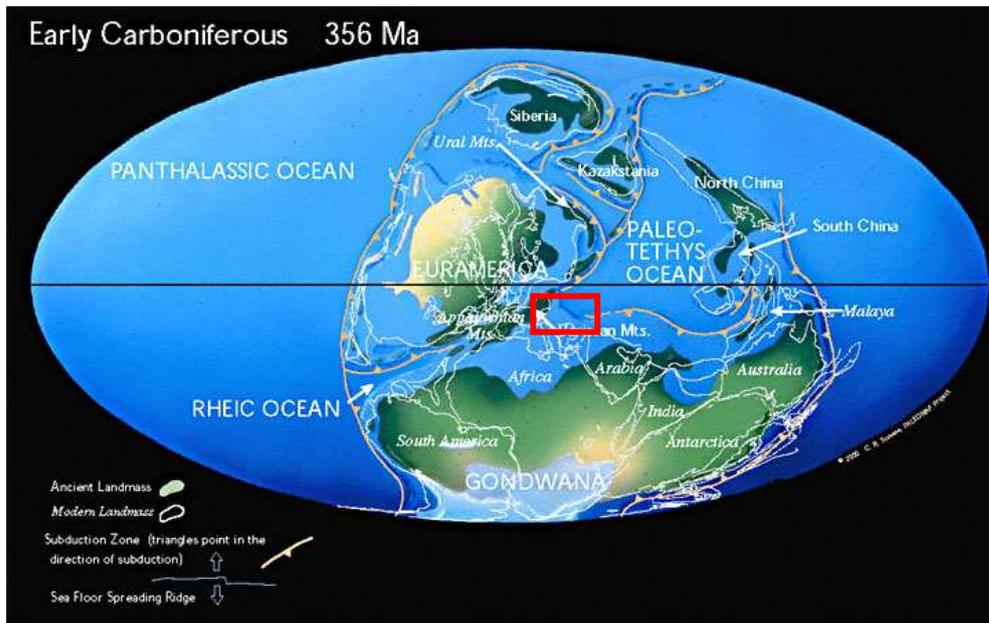


Figure.A-1. Lower Carboniferous palaeogeography, Scotese (<http://www.scotese.com>, accessed 15.02.2011). Red box: location of the UK.

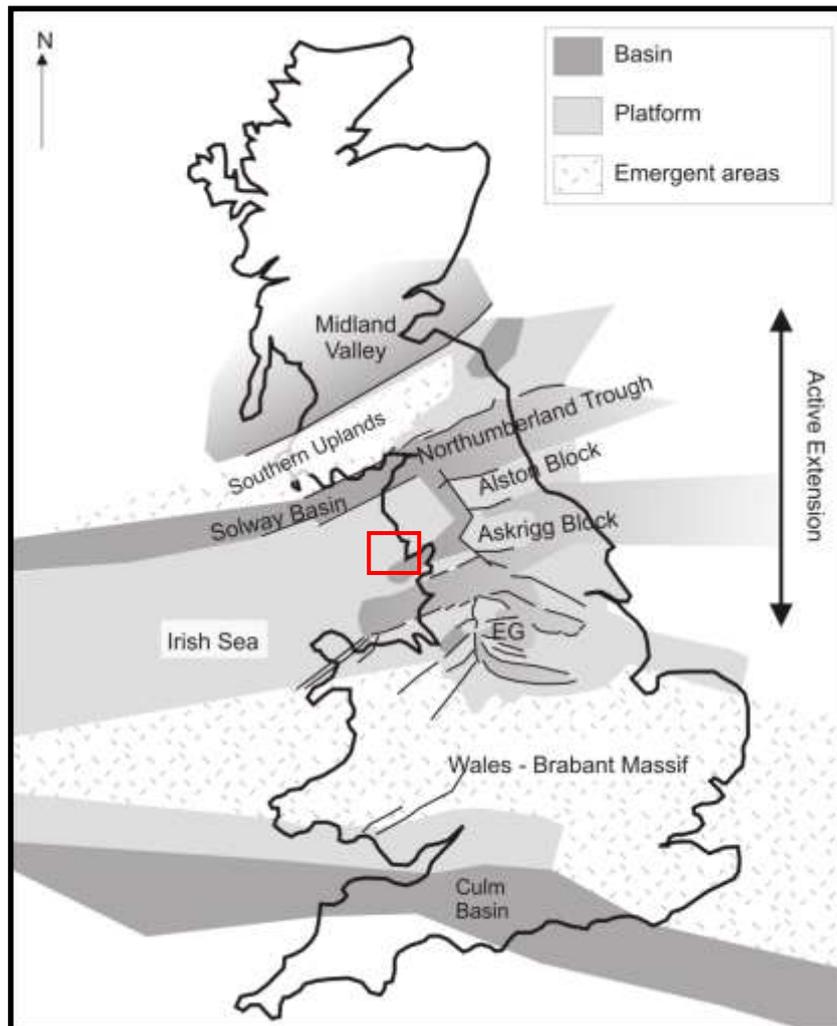
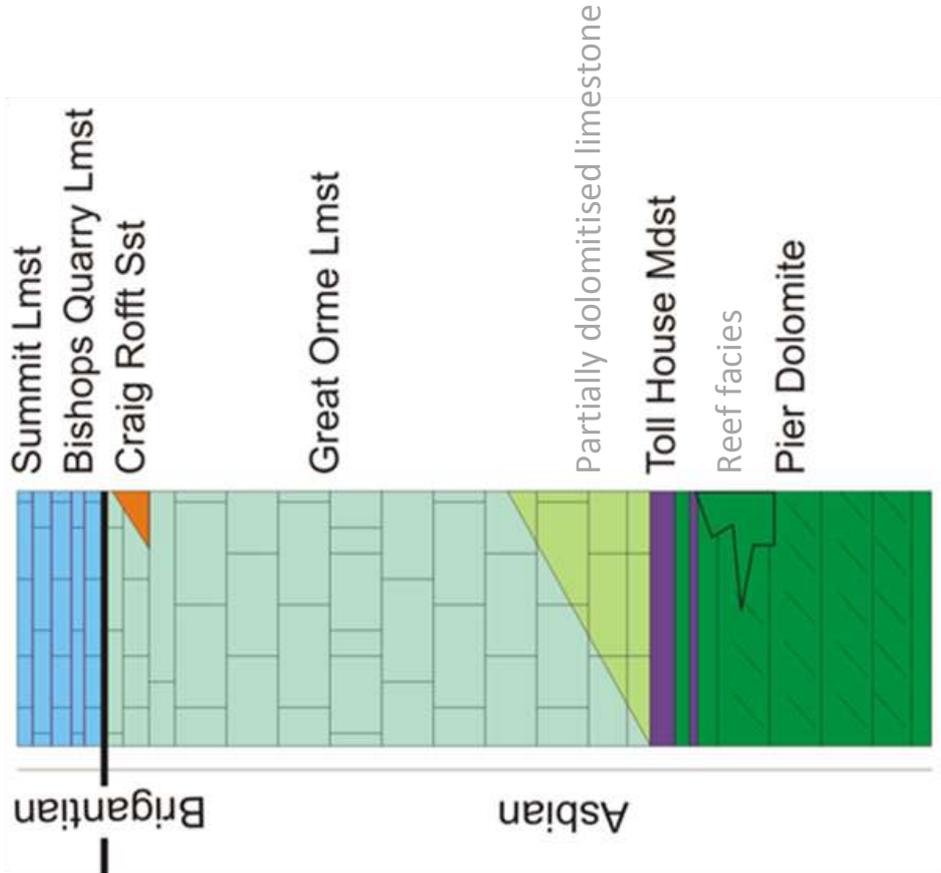
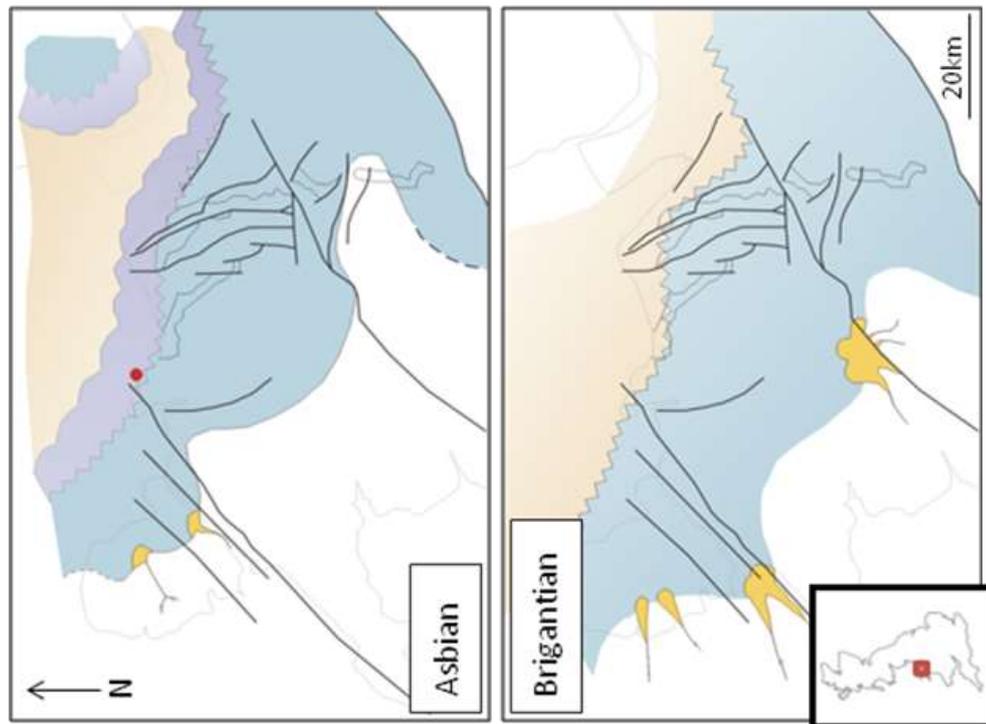


Figure.A-2. Schematic palaeogeography across UK and basin development within the Early Carboniferous (modified from Frazer and Gawthorpe, 1990). Red box indicates the study area and main lineaments within the Menai Straits Fault Zone

Figure.A-3. Schematic palaeogeography across North Wales and stratigraphic log for the Great Orme (modified from Waters and Davies, 2006). Red box: Great Orme. Purple: fringing reefs ; Blue: open carbonate platform; Brown: basin; Orange: fluvio-deltaic clastics'



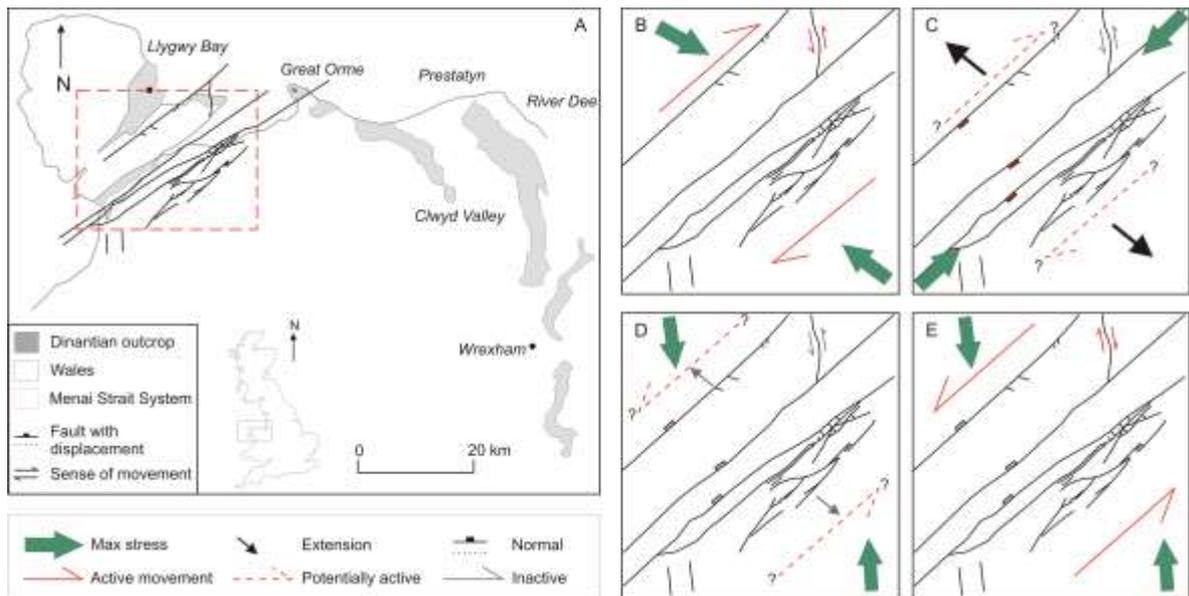


Figure.A-4. Summary diagram displaying the structural evolution of the Menai Strait Fault System from the Caledonian to the Cenozoic, A) Regional location map, North Wales; B) Pre-Cambrian-Caledonian compression and shear; C) Cambro-Ordovician extension and normal faulting; D) Carboniferous (early: extension with reversal in down-throw direction, late: Variscan compression and potential strike-slip reactivation of the shear zone) ; E) Tertiary-Cenozoic, Alpine compression and reactivation of fault systems with reverse and strike-slip movement. Figure from Juerges et al., in prep.

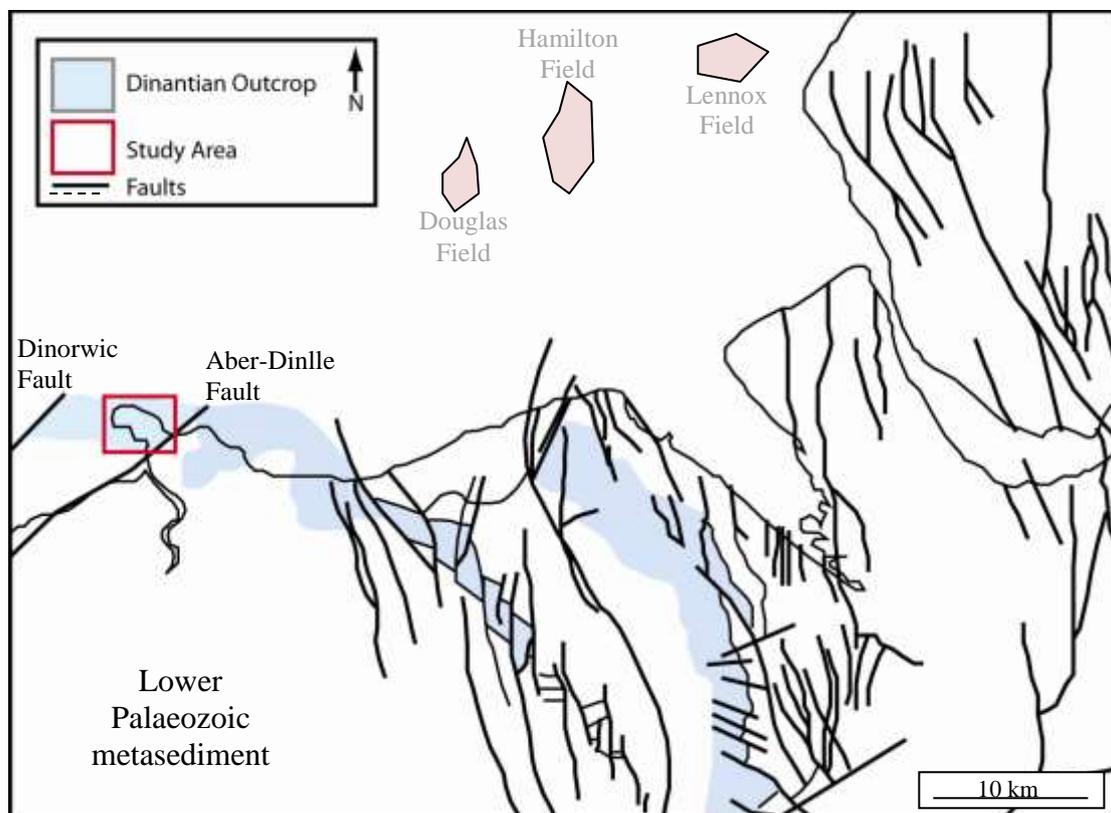


Figure.A-5 Map of faults within North Wales and the East Irish Sea Basin (modified from Williams and Eaton, 1993). Pink: oil and gas fields.

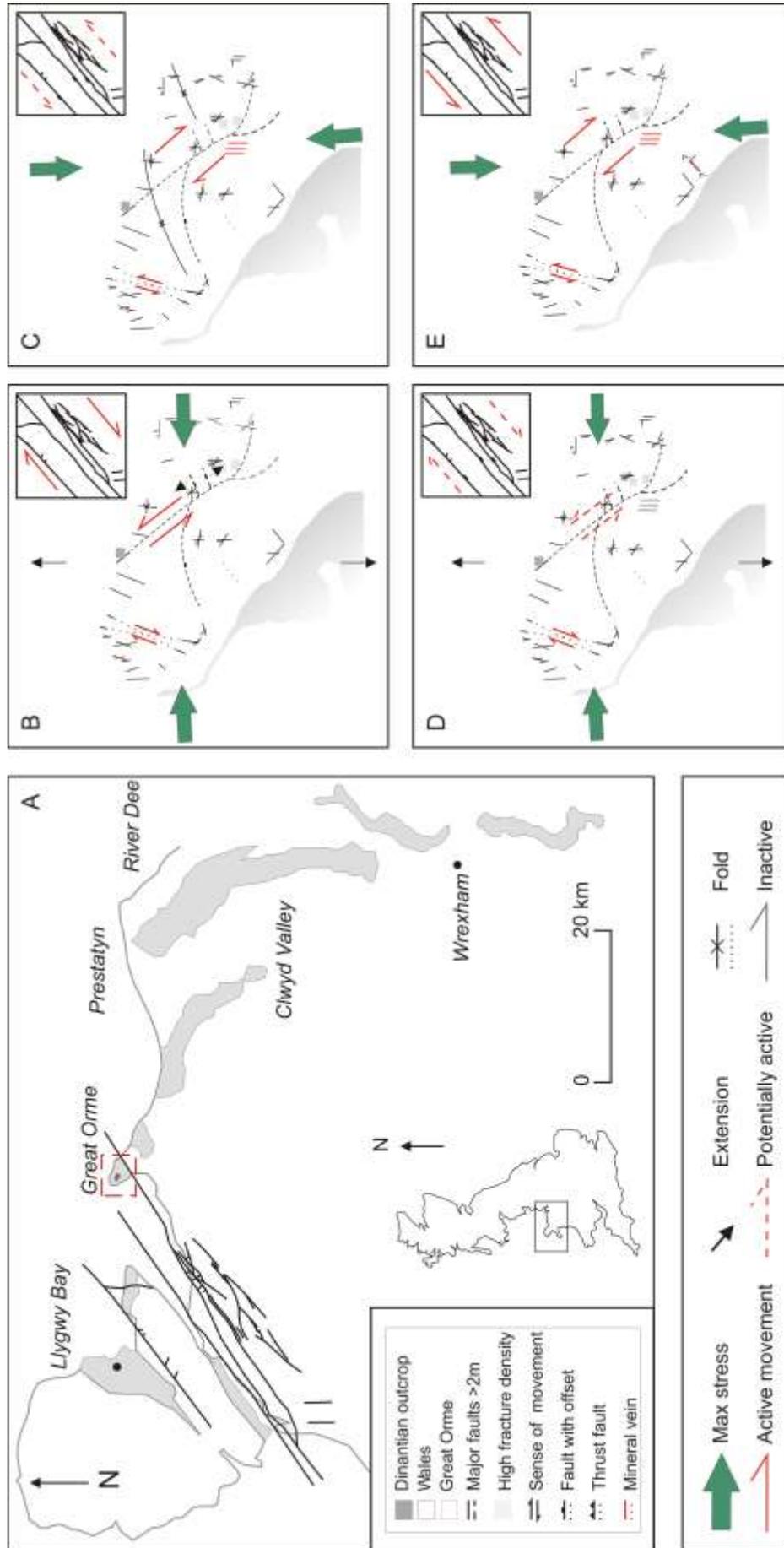


Figure.A-6. Summary diagram displaying the structural evolution of the Great Orme from the Early Carboniferous to the Tertiary, derived from field and petrographical observations tied in with the regional published data for the Menai Fault System (see figure 5), A) Regional location map, North Wales; B) Pre-early Carboniferous extension; C) Variscan compression; D) Permo-Triassic – Jurassic extension; E) Tertiary – Cenozoic Alpine compression. Figure from Juerges et al., in prep..

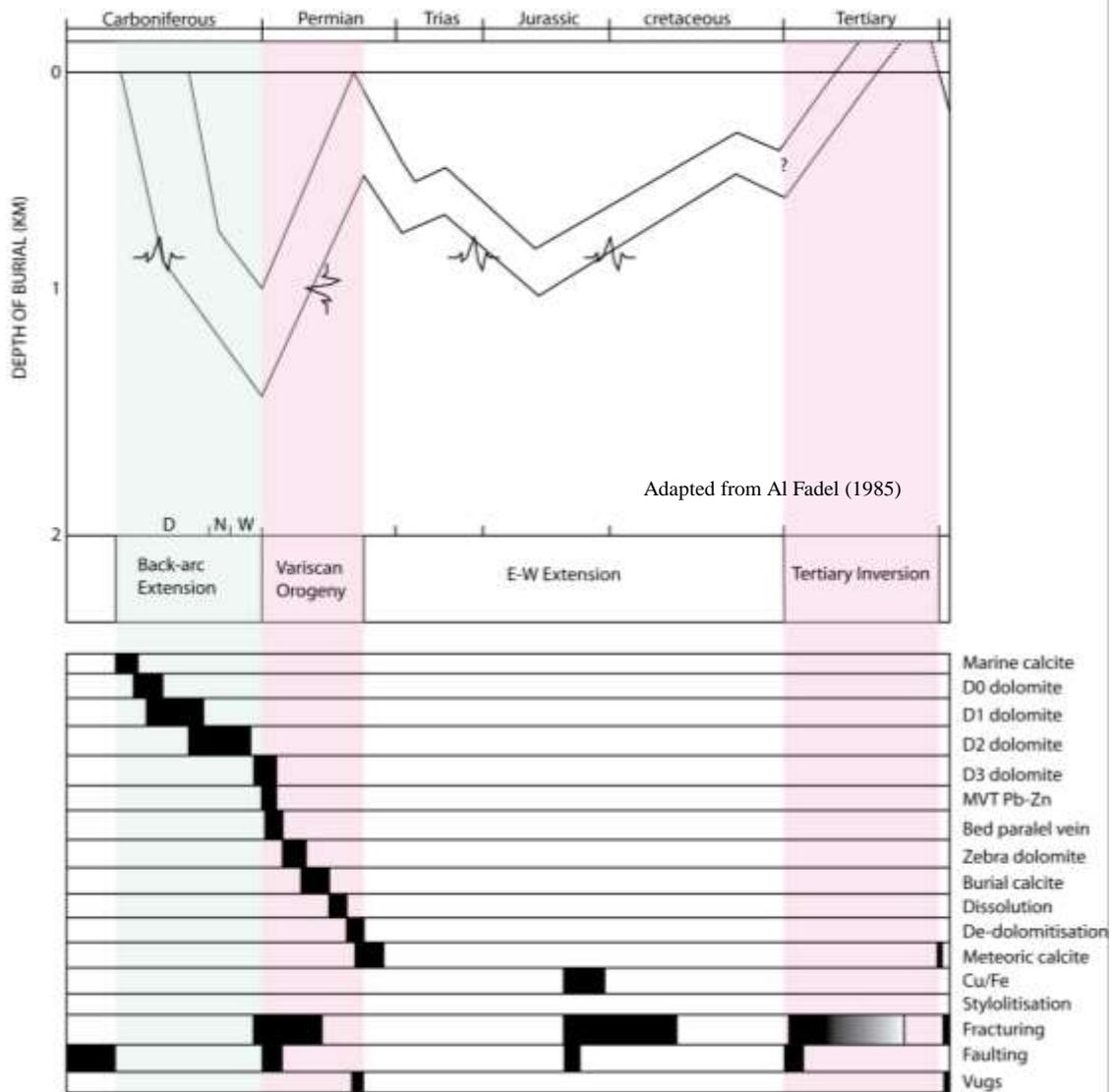


Figure. A-7. Summary diagram displaying the burial history and paragenesis for the Great Orme derived from field and petrographical observation.

Summary and Background

Prepared by Alanna Juerges (PhD, University of Manchester, 2013)

Introduction

The Great Orme is located at on the northern margin of the North Wales Platform. A platform that developed during the Lower Carboniferous (Dinantian/ Middle Mississippian/ Upper Visean), as a shallow marine shelf to the north of the low lying, but exposed, St Georges Land or Wales-Brabant Massif (George, 1974; Walkden and Davies, 1983). The base of the Carboniferous across North Wales forms an angular unconformity with the underlying Lower Palaeozoic (Ixer and Vaughan, 1993). Only upper Dinantian carbonates (Asbian and Brigantian) are exposed on the Great Orme. These are considered to form part of the palaeo-platform edge, which is approximately located along the present day coastline.

The Early Carboniferous of the Great Orme has been studied primarily for archaeological finds and the Bronze Age copper mines situated at the summit; there has been relatively little focus on its geology. The most comprehensive studies have been carried out by Oldham (1987), who assessed the reservoir potential of the dolomite through field observation; Lewis (1996) who reviewed the Great Orme geology and described the mineralisation; Williams and Eaton (1993) who carried out a structural study throughout North Wales, which included the Great Orme, and Parnell and Swainbank (1990) who calculated the timing of uraniferous bitumen deposits, of the Ty Gwyn mines, by lead (Pb-Pb) dating. Others general accounts have been published by Ramsbottom (1973); Smith (1973); Ramsbottom (1984).

The Great Orme is host to copper/ iron ore and minor amounts of Mississippi Valley Type (MVT) mineralisation. MVT deposits generally comprise galena and sphalerite with variable accessory assemblages including fluorite and barite amongst others (Bevins and Mason, 1999; Mason and Malpas, 2006). Such lead-zinc (Pb-Zn) dominated mineralisation is seen throughout the rest of the UK and is also referred to as Pennine Style Mineralisation (Parnell, 1992).

Palaeogeography

During the Early Palaeozoic, northern England and Wales were situated in a sub-tropical position on the Eurasian continent, north of the Rheic Ocean. In northern England, the Derbyshire and Askrigg Platforms, as well as the North Wales Platform, developed within a back-arc extensional regime to the north of the Wales-Brabant

Massif (Fraser and Gawthorpe, 1990). The North Wales Platform was attached to the Wales-Brabant Massif and was bounded to the north by the East Irish Sea Basin (Leeder, 1987, 1988; Wright *et al.*, 1997).

Platform geometry, facies distribution and palaeofluid flow (diagenesis and mineralization) were strongly influenced by the structural evolution of the northern UK. In particular, cessation of rifting and onset of compressional tectonism in the Upper Carboniferous exerted a major control on diagenesis and mineral emplacement (Wright *et al.*, 1997; Hollis and Walkden, 2002).

Structure

Situated on the southern periphery of the Pennine Basin during the Early Carboniferous, with major compressional belts to the south/ south-east during the late and post-Carboniferous, the Great Orme was subjected to multiple phases of faulting and folding into the Tertiary (Fraser and Gawthorpe, 1990; Turner 1997). The structures observed across the Great Orme follow predominantly Caledonian trends (NE-SW and an E-W structural grain) (Nichols, 1968; Wilson, 1968; Tremlett, 1970; Bassett, 1984; Lee *et al.*, 1990; Williams and Eaton, 1993). The headland is situated at the northern end of the Menai Straits Fault System, a Caledonian shear zone, and is bounded by the Aber-Dinlle Fault to the south and the Dinorwic Fault to the north; both these major faults had been active since the Cambrian. In addition, to the east of the Great Orme are the Gloddaeth Syncline and the Clwyd Fault System (Waters and Davies, 2004). Both systems display extensional – transtensional components (Tremlett, 1970; Reedman *et al.*, 1984; Williams and Eaton, 1993).

Through sedimentological and structural mapping it has been observed that there is a thicker Carboniferous carbonate succession on the Great Orme compared to that in the adjacent Gloddaeth Syncline. This probably resulted from deformation during the Variscan Orogeny (Williams and Eaton, 1993). Seismic sections to the north of the Great Orme display onlap of younger Jurassic sediment indicating that the Orme was most likely a post-Variscan structure (*op. cit.*). In addition, extensional faulting mapped from offshore seismic data also provides evidence of movement throughout the Carboniferous.

Faulting on the Great Orme has previously been described as having normal (cm – meter scale) offset with reactivation recorded by dip-slip movement. However, recent field observation suggests that strike-slip movement is more prominent at a local scale

than previously thought and potentially related to strike-slip reactivation along Caledonian trends on a regional scale. Observations include horizontal fault striations and a lack of variation in sediment thickness that would be expected across normal faults active during sedimentation. Further, high-angle conjugate fault and fracture systems with brecciation confined to the fault zones have been witnessed on multiple scales from aerial image (km-scale) to petrographical (mm-scale). The location and geometry of subsidiary structures can further be explained by local strike-slip fault movement on the Great Orme.

Stratigraphy

The Early Carboniferous (Dinantian) limestones unconformably overlie Lower Palaeozoic (Silurian) sediments with a sharp erosional contact (Davies *et al.*, 1989; Davies *et al.*, 2004). The oldest exposed Dinantian sediments (Tournasian-Arundian) on the North Wales Platform are not exposed on the Great Orme, where the oldest rocks are the Asbian Pier Dolomite.

Sedimentation in the Lower Dinantian took place on a gently sloping ramp. In the Asbian, this platform evolved into a flat-topped rimmed shelf (Walkden, 1987; Adams *et al.*, 1990). This relatively abrupt change has been attributed to syndepositional faulting, faunal evolution and/or to high frequency sea level oscillations as a result of growth of a major ice sheet within the southern hemisphere (Walkden, 1987; Vanstone, 1996; Waters and Davies, 2006).

The platform as a whole consists mainly of shallow marine carbonates, dominated by crinoidal packstones to grainstones. These were produced in relatively clear waters with little to no clastic input. High-frequency cyclicity is defined by metre-scale upward-shallowing successions of skeletal packstone and grainstone, capped by palaeo-karst, palaeosol and/or calcretes (Davies *et al.*, 2004). Sediments contain a diverse skeletal assemblage (e.g. benthic foraminifera, corals, echinoids, crinoids, brachiopods) indicative of sedimentation in clear, shallow water (Smith and George, 1961). The presence of shale horizons strongly suggests periodic inundations of clastic debris sourced from the Wales-Brabant Massif, which increased during the Brigantian (Somerville *et al.*, 1989). Petrographical observation from the current study demonstrates that not all shale horizons are composed of siliciclastic material; instead, many exhibit fine grained wacke-packstones textures.

Dolomitisation

Dolomitisation is observed across the Great Orme but is most pervasive at the base of the succession, in particular by Llandudno Pier. Two main types of dolomite have been recorded; pervasive replacement and fault/ fracture related dolomite. The first is the Llandudno Pier Dolomite initially described by Warren *et al.* (1984) and later by Oldham (1987) and Lewis (1996). The section was originally described as a stratiform deposit, 100m thick comprising vuggy and non-vuggy horizons of heavily altered Asbian platform limestone. The vugs are not only lined by dolomite but some also contain calcite (Warren *et al.*, 1984; Oldham, 1987). Oldham (1987) recorded porosity to be principally comprised of interconnected vugs, intercrystalline pore space and fractures. Porosity for the vuggy horizons is estimated to be about 15% and up-to 40% in areas of leaching and porosity within the non-vuggy horizons is unknown (*op. cit.*). However, the current study has determined that the vugs are isolated in most cases with matrix porosity in areas of sucrosic dolomite (up-to 10%).

The Pier Dolomite has previously been interpreted to have formed late in the burial history (Warren *et al.*, 1984). This interpretation has been tested by this study, which has focused on plain light and cathodoluminescence (CL), which reveal two generations of replacement; alteration of high magnesium (Mg) grains such as crinoid fragments (D0) followed by the volumetrically most important dolomite replacement, D1, xenotopic and sub-xenotopic fabrics creating an interlocking mosaic. The dolomite is only partially fabric retentive, occasionally displaying mimetic replacement but also preserving ghost structure of crinoid fragments. The crystals vary in size from 20 μm to 250 μm .

The Pier Dolomite outcrops at the base of the entire headland (2 by 3km, ~140m thick). Equivalent dolomite is seen only on the Little Orme 2km to the east. The exact vertical extent of the dolomite is unknown as underlying strata does not outcrop although Warren *et al.* (1984) documented Lower Palaeozoic basement lying unconformably below the Pier Dolomite. The precise geometry of the dolomite body is also difficult to determine due to limited exposure. However, field observation made around the beach record dolomite tongues extending into undolomitised limestone. These beds potentially represent the margins of the dolomite on the south-east margin of the Great Orme. Similar features have been recorded by Lewis (1996) from within the Great Orme Mines. The mines are located within the stratigraphically younger Great Orme Limestones. If these represent the lateral termination of the

dolomite and certain beds remain preferentially undolomitised, this would suggest that there may be a strong facies control on the location and lateral extent of the dolomite. Should the dolomite in the mines correspond to that on the beach then faults may be the dominant fluid conduits.

The second type of dolomite is the fracture controlled dolomitisation (D2-5). The dolomite is generally confined to the fractures (N-S and NE-SW) with only limited lateral penetration (cm-scale) into the host rock. The dolomite is seen within fractures cross-cutting the Pier Dolomite. Above Tollhouse Mudstone the only dolomite encountered is related to through-going faults and fractures.

D2 dolomite comprises euhedral, well-formed, inclusion rich, dark brown crystals often replacing D1 dolomite. However, D2 is completely fabric destructive and results in a completely interlocking mosaic. D3 saddle dolomite is inclusion rich with euhedral terminations and iron rich zones at the edges of the crystals. Following this, D4 indicates open space vein fill and growth and replacement of host rock with very coarse saddle crystals often featherlike in appearance but in all other respects is similar to D3. D5 is very late, coarse anhedral mosaic within the veins etching and partially replacing D4 dolomite crystal boundaries. D4 boundaries are preserved due to their iron rich composition, visible as inclusions within the replacing cement. D4 dolomite boundaries have also been seen to be replaced by calcite and quartz.

Table. 2. Summary table displaying the dolomite paragenesis derived from field and petrographical observation.

Cement	Morphology	CL	Extinction	Inclusion density	Inclusion type	Mineralisation	Distribution
D0	mimetic	medium pink/ red	unit	turbid	rare fluid	-	Echinoderm
D1	Planar-s	medium pink/ red	unit	turbid	fluid	-	Bioclastic wacke-packstones
D2	Planar-e	medium pink/ red	unit, undulose	turbid	Fe oxides	Fe oxides	D1 overprint, adjacent to extensional veins
D3	Planar-e, baroque	medium pink/ red	undulose	limpid	Fe oxides fluid	galena, sphalerite, minor barite	Extensional veins
D4	baroque	red	undulose	limpid	Fe oxides fluid	-	Extensional veins
D5	xenotopic	red	unit & undulose	limpid	-	chalcopyrite	Extensional veins and passive fill

Timing

The relative timing of the dolomitisation and associated diagenesis has been deduced from multi-scale cross-cutting relationships of fracturing, compaction features and mineralisation combined with the structural and burial history for the area.

The Pier Dolomite is overlain by, and has a clean sharp contact with, the Tollhouse Mudstone and unaltered, tight Asbian platform-limestone (Great Orme Limestone Fm). These in turn are overlain by tight Brigantian deeper-water limestones and interbedded shales (Bishops Quarry Fm and Summit Limestone Fm).

The control on the vertical extent of the Pier Dolomite is unresolved, resulting either from the overlying palaeokarstic surface or sealed by a subsequent marine shale interval. Determining the controlling factor would have a large bearing on the timing of the dolomitising event. Porosity within Dinantian strata was generally occluded early by meteoric-derived calcite cements, and if the palaeokarst surface was the dominant controlling factor then dolomitisation could have occurred early. If the shale interval acted as the seal, then dolomitisation could be much later (Oldham, 1987; Grayson and Oldham, 1987). Field and petrographical evidence suggest that the timing of the D0-2 events occurred relatively early in the diagenetic history at elevated temperatures. Evidence includes initial fabric retention in D0-1 followed by fabric loss with successive dolomitising events, change in textures from sub-xenotopic to well formed rhombic crystals with unit extinction and cross-cut by bed parallel stylolites that indicate D0-1 occurred before chemical compaction.

The subsequent fracture controlled D2-5 dolomite occur predominantly within N-S and NE-SW fractures that follow Caledonian and Variscan trends. Further constraint on the timing is evidenced by the cross-cutting relationship with bed parallel stylolites within the dolomitised host rock. Therefore, a relative timing of deep to post-maximum burial can be applied to the dolomite filled fractures. In addition, the textures seen in thin section, such as very coarse mosaics of saddle dolomite, indicate elevated temperatures. In many veins, cement bridges indicate precipitation on fracture opening. Zebra textures and veins along beds were likely to be related not only to strike-slip faulting but also high fluid pressures relating to flexure and folding during compression. The zebra textures and fault related dolomite have been attributed to the Variscan tectonics. These were then reactivated allowing for fluid of a different composition to deposit the copper and iron mineralisation and late diagenetic calcite within pre-existing fractures. In addition, fractures often display a

different orientation in maximum stress and cross-cut zebra textures. Reactivation on faults is supported by striations trending in multiple directions and minor reverse fault folds, a trend that is also recorded on regional structures. Following circulation and de-watering of the basin after the Variscan compression, the late calcite, re-mobilised dolomite and Cu/Fe mineralisation have been attributed to the Alpine tectonic in the Tertiary.

Potential fluid source

There have been multiple dolomitisation events identified on the Great Orme which raises the question of fluid source and volume. Further, the source of the Mg^{2+} responsible for the fluid enrichment and alteration has not been considered in any of the previous studies. The sources considered in this study, within the current tectonic and burial framework, include circulation of seawater and modified seawater to explain the formation of the Pier Dolomite and/or basinal brines for the late fracture related dolomite.

To summarise, the sequence of dolomitising events and postulated fluid sources are as follows. The first stage of dolomitisation by circulation of interstitial and marine fluids occurred probably before any significant compaction, forming the D0-1. The fluids received additional magnesium and carbonate with successive fluxes and a simple replacement process produced an interlocking dolomitic mosaic with destruction of primary texture and a reduction in porosity compared to that of the former packstones. The second episode of dolomitisation probably occurred after the very early dewatering had produced partial indurations of the sediments, sediments which had lost at least a fraction of their initial porosity (formation of D2). In this case, a prolonged circulation of marine fluids may have provided additional Mg and carbonate ions to induce not only replacement but also precipitation of dolomite (“overdolomitisation” of Lucia, 2004). The final episodes of dolomitisation probably occurred during the development of N-S orientated faults and fractures related to the Variscan Orogeny and development of folding throughout the Great Orme. The compression would have also provided a drive for modified basinal fluids to migrate through open flow conduits and permeable facies. Any subsequent fracture fill is likely to be a result of dolomite re-mobilisation (D5).

Diagenesis

The diagenesis of the Great Orme had not been described prior to this study. Furthermore, very few studies document the mineralisation and/or assess the occurrence in relation to the regional structural evolution. There have been no attempts to determine the timing, distribution or source of the precipitating fluids and consequently there is no published geochemical data available. The only known studies to date briefly document the occurrence of bitumen (Armstrong *et al.*, 1997) and the close spatial relationship between the copper mineralisation and the dolomites (Oldham, 1987; Lewis, 1996).

Set	Orientation	Cement	Mineralisation	Kinematic mode
1	N-S	dolomite	Cu-Fe-Pb-Zn	opening + mixed
	NNW-SSE	dolomite	-	opening + mixed
	NNE-SSW	dolomite	-	opening + mixed
2	E-W	calcite	-	opening
3	NW-SE	calcite and dolomite	Pb-Zn	opening + mixed
4	NE-SW	calcite	-	opening

Table 2. Summary table displaying the fault/fracture fills and structural paragenesis derived from field and petrographical observation.

Hydrocarbon

The predominantly uraniferous deposits have been recorded on The Great Orme in addition to the NE of Wales (Bevin and Mason, 1999). Samples analysed from The Great Orme Mines support the presence of uranium and sulphur, however, no thorium (Th) is present. Furthermore, only 0.1% constitutes zinc and the H/C are consistent with anthracite values (op cit.). Eakin and Gize (1992) have suggested that the lack of Th, below the limits of accurate detection, is a result of low temperature formation.

The Great Orme Mines and Northeast Wales Orefield have yielded hydrocarbon samples that do not contain sulphides but do comprise high concentrations of Cu (>1000 ppm) in close proximity to copper mineralisation (Parnell, 1983). The isotopic composition displays primarily heavy hydrocarbons (*c.* -25.0 per mill, carbon) and it has been postulated that the source maybe localised claystones within the Carboniferous limestone (Armstrong *et al.*, 1997).

Studies carried out by Parnell and Swainbank (1990) attempted to date the uraniferous bitumen at the Ty Gwyn mines, to the east of the Great Orme, through Pb-Pb techniques. The age determined for the migration and mineralisation associated with uraniferous bitumen is $248 \text{ Ma} \pm 21\text{Ma}$ (Early Triassic). The date is consistent with known hydrocarbon migration within the East Irish Sea Basin (Bushell, 1986).

In the absence of evaporates with the Carboniferous sediments of the Great Orme localised hydrocarbon may have provided a source of sulphur for the sulphide mineralisation and may also account for the very low volumes of Pb-Zn mineralisation (X.Marquez, pers. comm., 2011).

Acknowledgements

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References

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